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OBSERVATIONAL STUDY OF TRANSPORT IN THE FREE TROPOSPHERE

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16. ABSTRACT Anthropogenic pollutants such as acidic precursors, oxidants and particulates can arrive above a convective mixed layer by penetrative convective cloud activity (venting) or by air mass convergence. The development of improved long-range transport models will require consideration of the transport and dispersion processes in both the mixed and free tropospheric layers. These processes in the free troposphere are not adequately documented or understood and are generally ignored in current trajectory calculation schemes and source to receptor models. To address this problem, a technique to track free tropospheric pollutant transport was recently developed. The feasibility of using airborne lidar to observe the three-dimensional distribution of fluorescent dye particle (FDP) tracers in long-range atmospheric transport and dispersion studies as a candidate approach has been successfully demonstrated in field experiments conducted in the North East U.S. during October 1983. This approach uses a lidar system to excite non-toxic fluorescent dye particle (FDP) released into the atmosphere, and to monitor the emitted fluorescent light. When the lidar receiver is spectrally filtered, the fluorescent light can be detected separately from the elastic backscattered signal by background aerosols. On one occasion, an FDP cloud was released above the mixing layer, and subsequently tracked over more than 300 km. On another occasion, an initially-released circular tracer cloud reached an 8-to-1 (16-to-2 km) length-to width ratio two hours after release, and a 12-to-1 (30-to-2.5 km) length-to width ratio about four hours after release.

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OBSERVATIONAL STUDY OF TRANSPORT IN THE FREE TROPOSPHERE

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1. INTRODUCTION AND OBJECTIVES

Anthropogenic pollutants such as acidic precursors, oxidants and particulates can arrive above a convective mixed layer by penetrative convective cloud activity (venting) or by air mass convergence. These pollutants are then displaced along paths that are not necessarily horizontal, and can subsequently re-enter the mixed layer by either entrainment, subsidence, or in precipitating systems. The development of improved long range transport models will require consideration of the transport and dispersion processes in both the mixed and free tropospheric layers.

These processes in the free troposphere are not adequately documented or understood and are generally ignored in current trajectory calculation schemes and source to receptor models. This of course is primarily due to the nonavailability of adequate measurement techniques or air parcel tracking technology for this application. For example, tetroons are set to drift along constant density surfaces, however, free tropospheric transport is more likely to occur along isentropic surfaces. The use of chemical tracers require in situ sampling by aircraft, but logistical requirements make Lagrangian tracking extremely difficult on long range transport scales. Thus, adequate and precise verification data to test and validate model trajectory calculation schemes that for operational purposes utilize twice daily routine soundings from the synoptic scale network are unavailable up to this time.

To address this problem, a technique to track free tropospheric pollutant transport was recently developed as part of the National Acid Precipitation and Analysis Program (NAPAP). An airborne, two wavelength lidar, the ALPHA-1 system, Uthe (1983), was modified to track the movement of and to characterize the dispersion of a cloud of nontoxic fluorescent dye particles (FDP) in various release scenarios. This system is capable of range resolution of both a cloud of FDP particles and aerosol distribution, the latter for obtaining concurrent information on atmospheric stratification. Initial field tests of this system were conducted in conjunction with the Cross Appalachian Tracer Experiment (CAPTEX-83) tracer study. On several occasions, an FDP cloud was generated above the mixed layer in Ohio, and subsequently tracked by the ALPHA-1 system across the Appalachian mountains. The original circular cloud quickly elongated with travel distance but experienced relatively little lateral or vertical dispersion. This paper describes this technique in greater detail and presents and discusses examples of preliminary results of these transport experiments.

*On assignment from the National Oceanic and Atmospheric Administration, U. S. Department of Commerce.

2. METHODOLOGY

Rowland and Konrad (1979) have demonstrated a technique that uses a lidar system to excite fluorescent particles injected into the atmosphere. The lidar receiver is spectrally filtered to observe the fluorescent radiation and reject the radiation backscattered at the transmitted laser wavelength.

SRI International has demonstrated the use of an airborne lidar system in observing atmospheric transport and dispersion of fluorescent dye particle tracers. The Airborne Lidar Plume and Haze Analyzer (ALPHA-1) constructed and operated for the Electric Power Research Institute (EPRI) was used for this purpose.

The ALPHA-1 was constructed with a Nd:YAG laser transmitter and two independent receivers (Uthe, 1983). One measures the elastically backscattered radiation at the primary laser frequency of 1.06 μm and the doubled frequency of 0.53 μm; the other was modified to receive fluorescent light at 0.6 μm while rejecting the backscattered radiation at 1.06 μm and 0.53 μm. Thus, simultaneous mapping of a fluorescent dye particle (FDP) cloud and atmospheric aerosols can be achieved with the ALPHA-1 system.

Because the fluorescent spectrum is relatively large, a wide bandwidth filter was needed to pass the fluorescent signal. A wide bandpass filter, however, also passes a large amount of background (solar reflected) light. On the basis of ground tests, two interference filters were considered. One filter used a bandwidth of about 500 Å but also passed a small percentage of the elastic backscatter at 0.53 μm. The second filter had a 1500 Å bandpass and had more blocking at 0.53 μm but the increased background radiation resulted in a low overall signal-to-noise ratio.

Therefore, most of the data was collected with the 500 Å filter. The 1500 Å filter was used only on a convective cloud experiment where greater receiver rejection of the primary (0.53 μm) radiation was needed.

3. SAMPLE ANALYSIS OF TRANSPORT OBSERVATIONS

3.1 14 October 1983, 1802-2305 EDT

FDP-Cloud Track

On 14 October, a doughnut shaped cloud of fluorescent dye particles about 3/4 km diameter was released from Lancaster, Ohio (~45 km SE of Columbus) at 1750 EDT. Meteorological conditions were controlled by a high pressure system. Release height was 2290 m ASL nearly 900 m above the mixing layer, and in relatively dry air above a subsidence inversion. The ALPHA-1 tracked the FDP cloud over a distance of 327 km from Lancaster southeastward through West Virginia (Clarksburg) to just across the Shenandoah Mountains. At this point, the cloud became fragmented and could no longer be identified. The cloud trajectory (A-B and C-D) is shown in Figures 1 and 2. The lidar aircraft was refueled at B and contact with the FDP cloud was re-established at C. FDP-cloud altitude decreased from 2290 m ASL at release (A) to 1570 m ASL in the lee of the mountains (D).

Lidar Data

Figure 3 shows a gray-scale facsimile record of lidar data obtained over a 25-km horizontal distance approximately 230 km downwind from the FDP-release point (just before the high-elevation mountains shown in Figure 2). The upper part of the gray-scale presentation represents elastic backscatter data at 1.06 μm. It shows terrain contours, the mixing layer (about 900-1000 m thick), and the infrared backscatter from the FDP cloud at 2151 EDT, 2154 EDT, and 2157 EDT. The lower part shows terrain contours and the fluorescent backscatter at 0.6 μm received after the FDP cloud is illuminated by 0.53 μm (frequency doubled) laser radiation. No elastic backscatter from the atmospheric aerosol layers is received at this wavelength. The lidar data clearly demonstrate that the FDP cloud is transported above the mixing layer, and that its height above the terrain, its shape, and size can be accurately determined.

Meteorological Data

Meteorological analyses for the area of the FDP cloud were made using rawinsonde data from the network stations of Pittsburgh, Pennsylvania (PIT), Dayton, Ohio (DAY), Huntington, West Virginia (HTS), and Washington, D.C. (DCA) at the standard (release) time of 1900 EDT (2300 GMT). Upper-air observations near the average altitude of the cloud (2000 m ASL) were valid at about 1907 EDT. This time is associated with the location of the FDP cloud at the point E indicated in Figures 1 and 2.

The temperature, pressure, and wind at the point E were determined by linear interpolation of the rawinsonde data from PIT and HTS. Thus, these quantities characterize an air parcel at the location of the FDP-cloud at 1907 EDT. The trajectory of this air parcel was computed on the isentropic surface corresponding to the

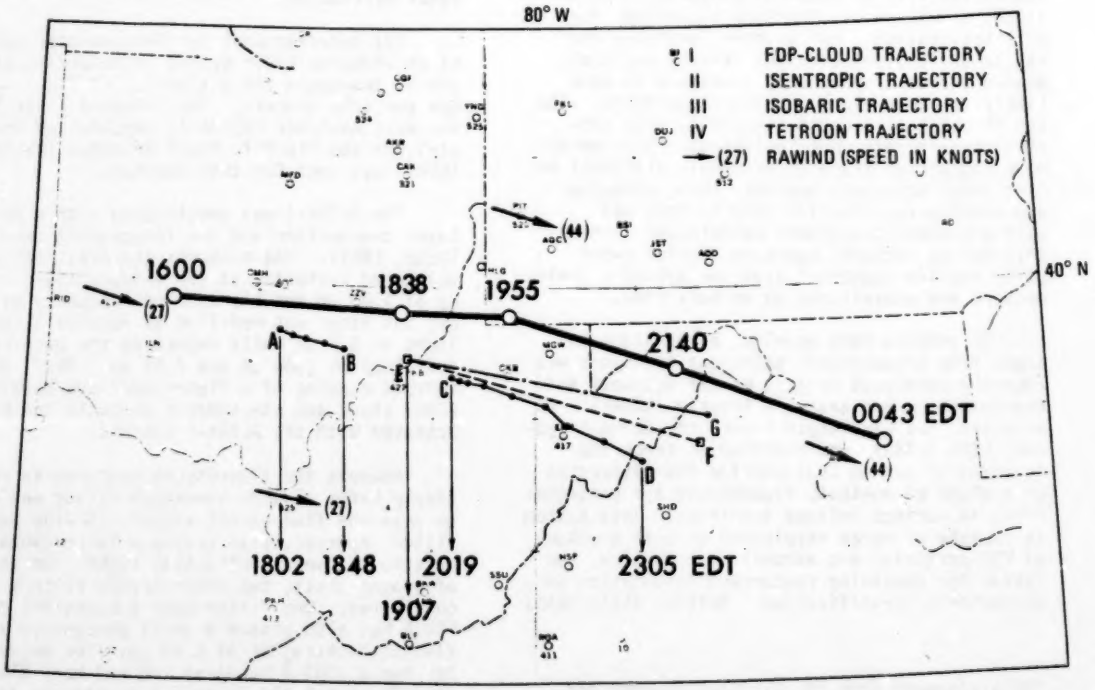

Figure 1. Observed FDP-cloud trajectory (A-B and C-D), I, compared with II, computed isentropic air trajectory (E-F), and III, isobaric trajectory (E-G). Tetroon trajectory is indicated as IV.

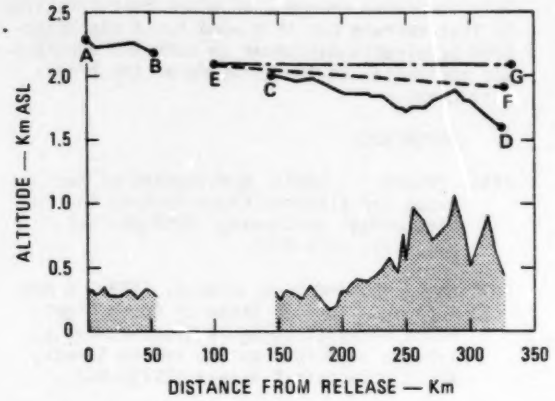

Figure 2. Vertical plane of observed FDP-cloud trajectory (A-B and C-D) with underlying terrain contour. E-F and E-G represent computed air-parcel trajectory on the isentropic and isobaric surface, respectively, starting on the FDP-cloud track at the point E (14 October 1983, 1802-2305 EDT).

potential temperature at E (θ = 295°K) and on the isobaric surface corresponding to the pressure at E (P = 794 mb).

Air Parcel Trajectories

Using the rawinsonde data of PIT, DAY, HTS, and DCA, the field of the Montgomery streamfunction for θ = 295°K was analyzed, and the isentropic trajectory starting at point E was constructed for the nearly 4-hour time period extending from 1907 EDT till 2305 EDT (The end time of the FDP-cloud track at D). Similarly, the isobaric surface of P = 794 mb was analyzed in terms of height contours and an isobaric trajectory was computed starting at E also.

Figure 1 shows the trajectory comparison in the horizontal plane. The dashed line E-F represents the computed isentropic air trajectory. It terminates at F about 52 km northeast of the FDP track endpoint D. The average transport speed along the isentropic trajectory is 36 knots. The dash-dot line E-G represents the isobaric trajectory. It terminates at the point G which is 24 km north of F. The average velocity along the isobaric trajectory is 36 knots. Its general direction (279°) is more westerly than that of the isentropic path (284°). The isentropic air trajectory agrees quite favorably with the FDP track except during the second half of the time period when the FDP track veers about 10° toward the south, which could be interpreted as a recurvature induced by the mountains. The heavy line in Figure 1 indicates the path of a tetroon released at Dayton, Ohio at 1500 EDT. The various times of the tetroon position are shown along its track.

Figure 2 shows the trajectory comparison in the vertical plane together with the underlying terrain topography. The general descent of FDP cloud is evident as well as its up-and-down transport across the mountains. The computed isentropic trajectory shows a gradual descent; the isobaric trajectory does not show any descending motion.

From their common location at E, the trajectories diverge in both the vertical and horizontal plane. The observed small-scale features of the FDP trajectory in comparison with the computed synoptic-scale air-parcel trajectories are most evident in Figure 2. Table 1 summarizes the overall trajectory characteristics.

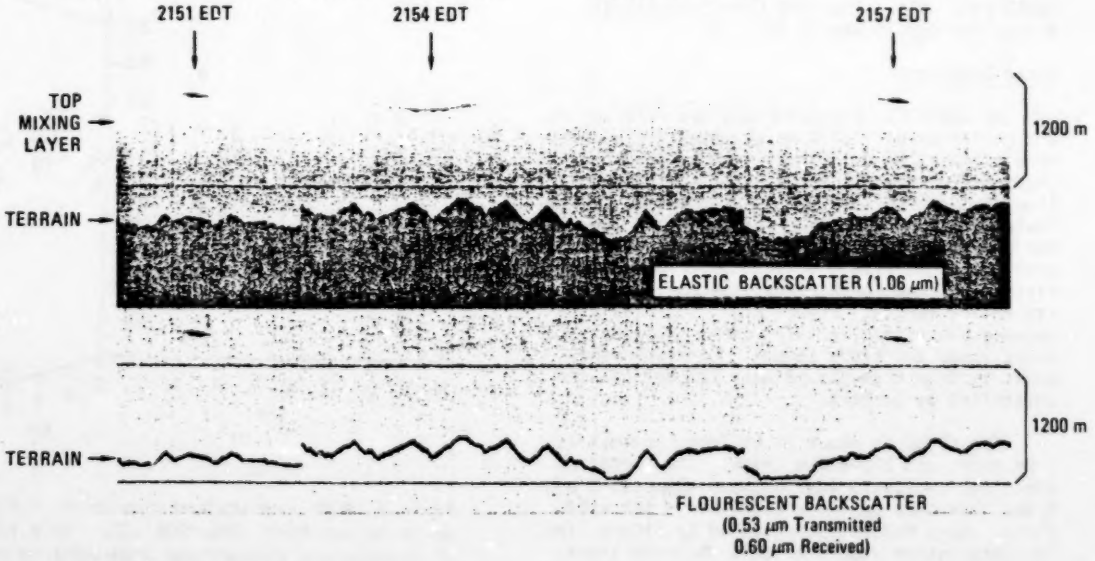

Figure 3. Gray-scale facsimile record of lidar data (elastic backscatter at 1.06 μm and fluorescent backscatter at 0.6 μm) showing FDP cloud above the mixing layer at three different times (14 October 1983, 2144-2201 EDT).

Table 1.

TRAJECTORY CHARACTERISTICS

Trajectory	Mean Horizontal Transport: Direction (Degrees)	Mean Horizontal Transport: Velocity (knots)	Mean Vertical Transport* (cm sec^{-1})
FDP	290	35	-4.3
Isentropic	284	36	-1.0
Isobaric	279	36	0

*Negative represents descending motion.

3.2 16 October 1983, 1650-2359 EDT

FDP-Cloud Track

On 16 October, an FDP cloud was released from Delaware, Ohio (about 40 km north of Columbus) at 1650 EDT. A high pressure system prevailed in the area. Release height was 2300 m ASL about 500 to 800 m above the mixed layer. Relative humidity at this level was 10-20%. The cloud was tracked by the ALPHA-1 over a distance of 236 km through eastern Ohio to a point between Youngstown, Ohio and New Castle, Pennsylvania. No mountain traverse took place; underlying terrain elevation varied between 274 and 305 m (900-1000 ft ASL).

Meteorological Analysis

The synoptic-scale analysis obtained from rawinsonde data available at 1907 EDT showed a trough in the streamlines of the wind at the FDP-cloud altitude. The troughline extended across the cloud track at the time that the FDP-cloud structure was identified by ALPHA-1 (1845-1908 EDT). The wind direction change across the trough was 13-22°.

Cloud Structure

At 1650 EDT, the FDP cloud was released in a circular shape of 3/4 km diameter and a thickness of about 50 m. Figure 4 shows the cloud shape as observed by the ALPHA-1 during the time period 1845-1908 EDT (near the time of the rawinsonde data). Figure 4(a) is a top view of the cloud. It shows successive cross-sectional areas obtained from the lidar observations while flying back and forth across the FDP cloud along its entire length. Figure 4(b) is a side view showing successive vertical cross-sectional areas along the cloud length. Corresponding cross-section elements between (a) and (b) are identified by numbers.

The cloud is about 16 km long, as much as 2 km wide, and 100-200 m thick. The "bend" in the cloud in Figure 4(a) between elements 1 and 5 may have been on the troughline in the wind field. Wave motion is indicated by Figure 4(b). The interesting aspect of this observed transport case is the rapid along-wind stretching of the FDP cloud from its initial 3/4-km diameter circular shape to an elongated shape with an 8-to-1 (16-to-2 km) length-to-width ratio. This structure change took place over relatively flat terrain but in a wind field characterized by directional shear in both the vertical and horizontal at the altitude of the transport event.

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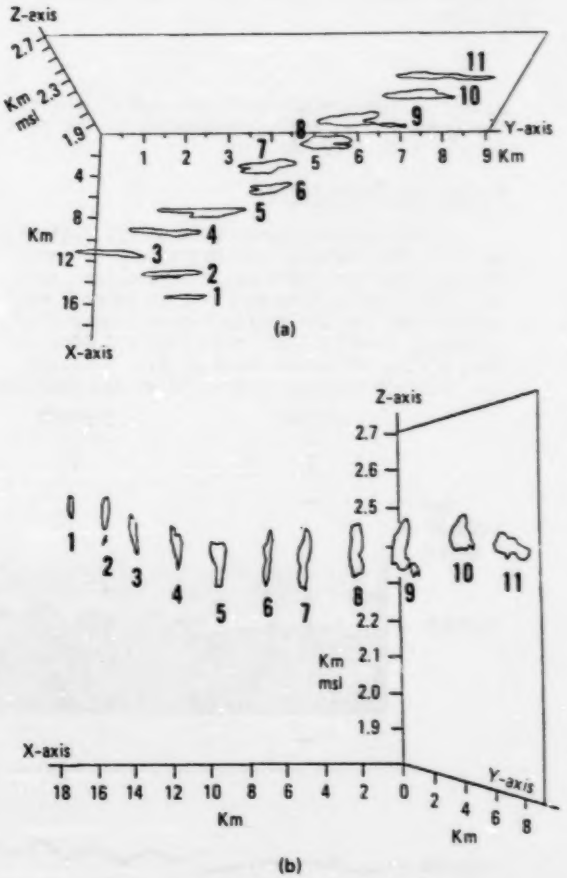

Figure 4. FDP-cloud structure observed by ALPHA-1 on 16 October 1983, 1845-1908 EDT. (a) is top view of cloud showing cross-sectional areas along the length of the cloud in the X-Y plane. (b) is side view of cloud showing cross-sectional areas in the vertical X-Z plane. Corresponding elements of (a) and (b) are numbered.